

INVERSE-COMPTON GAMMA RAYS IN THE GALAXY

J.B.G.M. Bloemen

Laboratory for Space Research Leiden

P.O. Box 9504, 2300 RA Leiden, The Netherlands

1. Introduction. Various studies of the high-energy (≥ 50 MeV) gamma-ray observations obtained by the SAS-2 and COS-B satellites have indicated that the major part of the galactic gamma-ray emission should most probably be attributed to cosmic-ray-matter interactions in the interstellar medium. Correlation studies between the observed distributions of the gamma-ray intensity and the interstellar gas density therefore give insight into the distribution of cosmic-ray (CR) particles throughout the Galaxy (see e.g. Bloemen et al., OG3.1-6). An additional contribution to the observed diffuse gamma-ray emission, however, originates from the interaction of CR electrons with interstellar photons through the inverse-Compton (IC) process. Several authors have studied this component (e.g. Cowsik and Voges, 1974; Shukla and Paul, 1976; Piccinotti and Bignami, 1976; Bignami and Piccinotti, 1977; Kniffen and Fichtel, 1981), but the uncertainties were large since only limited information on the interstellar photon field throughout the Galaxy was available. Most works showed the IC contribution to be small (particularly outside the very central region of the Galaxy), but Kniffen and Fichtel (1981) concluded from the most detailed analysis until now that the IC radiation may account for a significant part of the observed gamma-ray emission from the inner Galaxy.

Compton gamma rays with energies > 1 MeV largely result from scattering between electrons, with energies > 100 MeV, and photons in the optical and infrared range and the 2.7 K universal blackbody radiation. This paper presents an empirical model of the IC gamma-ray production in the Galaxy, using the most recent estimate of the interstellar electron spectrum given by Webber (1983) and a combination of optical and infrared observations to determine the galactic distribution of the various components of the interstellar photon field. Compared to previous works, the present analysis has a significantly improved precision since the spectral distribution of the IC source function as well as that of the interstellar photon field are more accurately taken into account. In addition, the exact evaluation of the IC process is applied and different electron distribution models are considered. A detailed description of the work is given by Bloemen (1985).

2. The source function of the IC process. The general evaluation of the IC mechanism (based on the exact Compton cross section; Klein-Nishina formula), as discussed by e.g. Blumenthal and Gould (1970), is applied. The generally applied Thomson approximation is not appropriate, because it leads to serious overestimation of the gamma-ray production above ~ 100 MeV for a large part of the photon field (Schickeiser, 1979) and because the electron spectrum shows a continuous steepening with increasing energy, that cannot accurately be taken into account in the Thomson limit. The volume emissivity S of gamma rays with energy E_γ produced by IC scattering of electrons and target photons with energy ϵ and energy density $u(\epsilon, \vec{r})$, at position \vec{r} in the Galaxy, is given by

$$S(E_\gamma, \vec{r}) = \int_0^\infty s(E_\gamma, \epsilon, \vec{r}) u(\epsilon, \vec{r}) d\epsilon \quad (\text{ph cm}^{-3} \text{ s}^{-1} \text{ MeV}^{-1}), \quad (1)$$

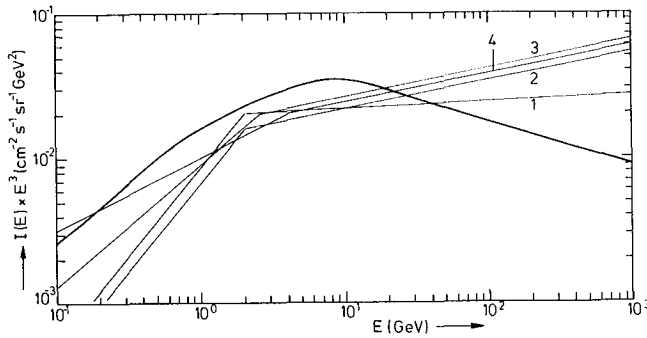


Figure 1: The local interstellar electron spectrum used in the present analysis (thick line), taken from the review of Webber (1983). The thin lines indicate electron spectra used in previous IC studies: (1) Shukla and Paul (1976), (2) Piccinotti and Bignami (1976), (3) Kniffen and Fichtel (1981), and (4) Fichtel and Kniffen (1984).

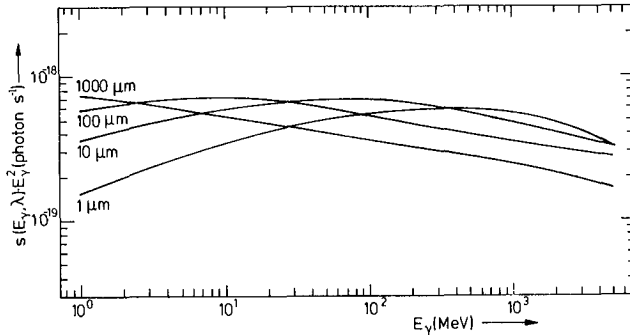


Figure 2: The differential local IC gamma-ray source functions as a function of gamma-ray energy for selected wavelengths of the target interstellar radiation field (E_γ^2 in MeV^2).

where s is the IC source function, depending on the CR electron spectrum. The local electron spectrum is taken from the review of Webber (1983) (Figure 1). Figure 2 presents the resultant IC source function for some selected wavelengths of the interstellar radiation field. The IC production of gamma rays above ~ 50 MeV, on which this analysis is concentrated, is entirely due to electrons with energy $E > 1$ GeV (and for the far-infrared target photons only to electrons with $E > 10$ GeV). Therefore, the uncertainties in the electron spectrum below ~ 400 MeV are of only minor importance.

Only very little is known about the variation of the spectral distribution of electrons with position in our Galaxy nor in other Galaxies. There are no strong indications for large-scale variations of the spectral shape from low-frequency radio observations, but these observations are restricted to the low-energy part of the electron spectrum. For the high-energy part, synchrotron and IC losses, which vary throughout the Galaxy, may produce spectral differences. It is assumed in this paper that the spectral shape does not strongly vary throughout the Galaxy. On this assumption, large-scale variations of the CR electron density in the Galaxy can be accounted for by an absolute scaling of the local electron spectrum, and the same scaling applies then to the IC source function.

3. The interstellar photon field. The interstellar radiation field from the UV to the mm range can be thought of as being composed of three components, each governing different parts of the spectrum. The UV, optical, and near-infrared ranges of the spectrum ($0.1 \mu\text{m} \leq \lambda \leq 8 \mu\text{m}$) are dominated by direct stellar emission. The emission in the mid- and far-infrared region ($\lambda \geq 8 \mu\text{m}$, up to wavelengths in the submm range) is nearly entirely from dust grains. The third component is the 2.7 K universal blackbody background at an average wavelength of ~ 2 mm, with an energy

Table 1: Total IC emissivities at characteristic locations in the Galaxy. The electron spectrum is assumed to be equal to the local spectrum at each position (see Section 4).

E(MeV)	z(kpc)	S(photon cm ⁻³ s ⁻¹ MeV ⁻¹)				
		R = 3 kpc	R = 5 kpc	R = 8 kpc	R = 10 kpc	R = 13 kpc
1	1.0		4.8 10 ⁻²⁵		2.6 10 ⁻²⁵	
	0.5		6.5 10 ⁻²⁵		2.8 10 ⁻²⁵	
	0	7.2 10 ⁻²⁵	1.2 10 ⁻²⁴	5.9 10 ⁻²⁵	3.5 10 ⁻²⁵	2.3 10 ⁻²⁵
10	1.0		6.3 10 ⁻²⁷		2.6 10 ⁻²⁷	
	0.5		9.3 10 ⁻²⁷		3.0 10 ⁻²⁷	
	0	1.0 10 ⁻²⁶	1.6 10 ⁻²⁶	7.3 10 ⁻²⁷	4.0 10 ⁻²⁷	2.2 10 ⁻²⁷
100	1.0		6.7 10 ⁻²⁹		2.3 10 ⁻²⁹	
	0.5		1.0 10 ⁻²⁸		2.8 10 ⁻²⁹	
	0	1.1 10 ⁻²⁸	1.7 10 ⁻²⁸	6.9 10 ⁻²⁹	3.8 10 ⁻²⁹	2.0 10 ⁻²⁹
1000	1.0		5.7 10 ⁻³¹		1.9 10 ⁻³¹	
	0.5		9.2 10 ⁻³¹		2.3 10 ⁻³¹	
	0	9.5 10 ⁻³¹	1.4 10 ⁻³⁰	5.6 10 ⁻³¹	3.1 10 ⁻³¹	1.7 10 ⁻³¹

density of $\sim 0.25 \text{ eV cm}^{-3}$. For the first two components, the energy densities were derived by empirical modelling of the interstellar photon field throughout the Galaxy, as described by Bloemen (1985), based on the work of Mezger et al. (1982) and Mathis et al. (1983). The dust absorption is taken into account.

4. IC gamma-ray emissivities and comparison with observations. Following equation (1), the galactic distribution of the IC volume-emissivity spectrum has been determined. Table 1 presents the IC emissivities for some characteristic locations and gamma-ray energies. At each position the electron spectrum is adopted to be equal to the local spectrum; scaling is required (Section 2), depending on the actual electron density distribution.

Various analyses of the low-frequency radio surveys indicate a scale height for the synchrotron volume emissivity of typically 0.5-1 kpc in the inner Galaxy (but significantly higher in the outer Galaxy) and a radial scale length of ~ 4 kpc (e.g. Baldwin, 1976; Brindle et al., 1978; Phillipps et al., 1981; Beuermann et al., 1985). Since the corresponding electron distributions are uncertain, three simple electron distribution models have been considered to investigate the impact of these uncertainties on the predicted IC intensity distributions, namely:

- (a) $w(R,z) = e^{-z/z_0}$ ($z_0 = 750 \text{ pc}$)
- (b) $w(R,z) = 1$ for $|z| < 1 \text{ kpc}$ and $w(R,z) = 0$ for $|z| > 1 \text{ kpc}$
- (c) $w(R,z) = (1+(R_0-R)/5)e^{-z/z_0}$ ($z_0 = 750 \text{ kpc}$; $R_0 = 10 \text{ kpc}$),

where w describes the galactic distribution of the electron density relative to the local ($R = 10 \text{ kpc}$, $z = 0$) density. The electron density outside 15 kpc was adopted to be zero. The linear increase towards the galactic centre in case (c) was chosen as a most simple description of a CR gradient with a density at $R = 5 \text{ kpc}$ that is ~ 2 times larger than in solar vicinity, as indicated by the radio observations mentioned above and also by the gamma-ray observations (e.g. Bloemen, OG 3.1-6).

Figure 3 presents longitude and latitude distributions of the predicted IC intensities, for the three electron distribution models, and of the COS-B observations, for three different gamma-ray energy ranges. In the galactic plane, the IC contribution to the observed intensities for the three energy ranges does not in general exceed 5% for the different electron models considered. At medium latitudes ($|b| \approx 15^\circ$) the

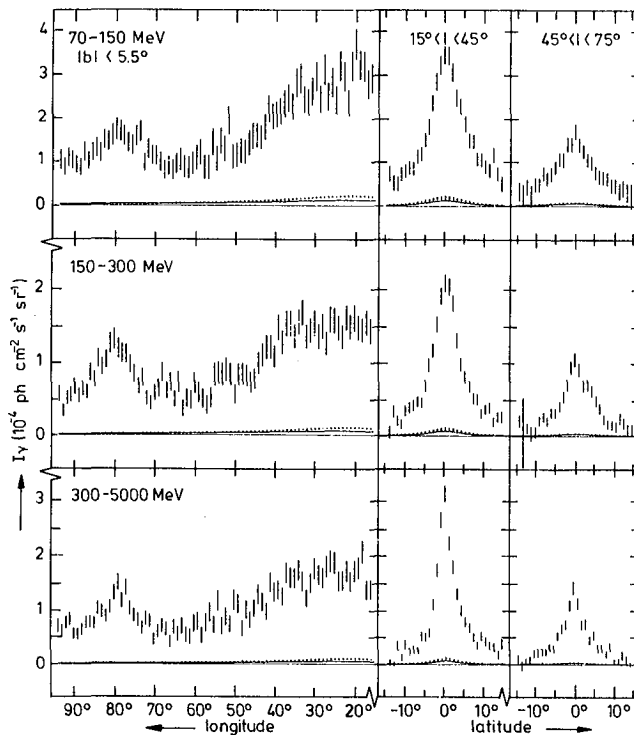


Figure 3: Longitude and latitude profiles of the predicted IC gamma-ray intensities and the COS-B observations (1σ statistical error bars). The thin horizontal lines indicate the zero level. The IC intensities are shown for three electron distribution models (see Section 4): thick full line, model (a); thin dotted line, model (b); thick dotted line, model (c). In some figures the individual curves are hardly visible, indicating the minor differences compared to the observed intensities.

IC contribution is higher due to the large scale height of the IC emission compared to that of the gamma-ray emission from CR-matter interactions, but remains still less than $\sim 10\%$. The IC contribution in the inner Galaxy is probably even smaller than estimated above due to the effect of the IC production on the CR electron spectrum (i.e. a steepening of the high-energy part of electron spectrum due to Compton losses). For the outer Galaxy the IC intensities are negligible.

The IC gamma-ray luminosity of the Galaxy above 100 MeV is found to be in the range $(1.0-1.5) \times 10^{41}$ ph s $^{-1}$ for all three electron distribution models, which is an order of magnitude smaller than the gamma-ray luminosity of the CR-matter interactions.

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